Tectonics of the Deccan Large Igneous Province: an introduction

SOUMYAJIT MUKHERJEE[1]*, ACHYUTA AYAN MISRA[2], GÉRÔME CALVÈS[3] & MICHAL NEMČOK[4,5]

[1]*Department of Earth Sciences, Indian Institute of Technology Bombay, Mumbai 400 076, Maharashtra, India*

[2]*Exploration, Reliance Industries Ltd, Mumbai 400 701, Maharashtra, India*

[3]*Université Toulouse 3, Paul Sabatier, Géosciences Environnement Toulouse, 14 avenue Edouard Belin, 31400, Toulouse, France*

[4]*EGI at University of Utah, 423 Wakara Way, Suite 300, Salt Lake City, UT 84108, USA*

[5]*EGI Laboratory at SAV, Dúbravskácesta 9, 840 05 Bratislava, Slovakia*

**Correspondence: soumyajitm@gmail.com*

Many questions have been raised about the tectonic controls and structural evolution of the large igneous provinces (LIPs) of the world; these provinces are of enormous interest to tectonicians (see recent review by Ernst 2014) and the Deccan Traps are no exception (e.g. Dessai & Bertrand 1995; Peshwa & Kale 1997; Collier *et al.* 2008; Corfield *et al.* 2010; Hooper *et al.* 2010; Calvès *et al.* 2011; Dixit *et al.* 2014; Misra 2015; Misra *et al.* 2014, 2015, **2016**; Misra & Mukherjee 2015). The Deccan large igneous province (DLIP) (the Deccan Traps) is the product of the voluminous outpouring of mainly basaltic lavas at the Cretaceous–Tertiary (K–T) boundary and constitutes one of the largest known LIPs in the world (Bryan *et al.* 2010). The Deccan Volcanic Province (DVP) covers >500 000 km^2 (Watts & Cox 1989; Deshpande 1998; Chandrasekharam 2003 and references cited therein; see reviews by Vaidhyanadhan & Ramakrishnan 2008; Philpotts & Ague 2009). Pre-erosion estimates for the area covered by the lavas vary widely, but are typically $1–2.6 \times 10^6$ km^2 (Chandrasekharam 2003 from references cited therein; Vaidhyanadhan & Ramakrishnan 2008). The total thickness of the Deccan Traps exceeds 2000 m (Kaila *et al.* 1981; Deshpande 1998; Harinarayana *et al.* 2007). The Deccan Traps are one of the most important LIPs in studies of the origin and eruption of large volumes of basaltic magma since the Mesozoic.

The Deccan volcanism produced outpourings of lavas over an extended period of time from *c.* 68 to 60 Ma (reviews by Pande 2002; Chenet *et al.* 2007 and references cited therein; Hooper *et al.* 2010; Valdiya 2010, 2011; Baksi 2014), possibly in pulses (Chenet *et al.* 2007). Peak volcanism occurred at *c.* 65 ± 0.5 Ma (Chenet *et al.* 2007; review by Valdiya 2010). Most of the research on the onshore part of the DLIP has focused on the lithology, geochemistry, isotopic ages and overall relationship of the volcanism with continental rifting. Organized studies on the tectonic structure of the underlying continental lithosphere, the structural development of the volcanic province and the post-eruption tectonic development of the province have been relatively undocumented, pending fresh studies (e.g. Misra *et al.* 2014). The western DLIP is an exposed passive continental margin and is a globally significant example of a volcanic margin, crucial in our understanding of the dynamics of such margins. The offshore areas of the passive margin have been investigated using single-channel and seismic refraction studies, although none of these studies has produced images deep enough to image the entire crust. New data from many sources have now been made available (Misra *et al.* 2015, **2016**). This book presents further research in the onshore and offshore passive margin regions. The northern areas of the DLIP in Kutch (Gujarat, India) are highly active and the central parts are moderately active in terms of present day deformation manifested by recurring earthquakes, possibly related to the ongoing Himalayan orogeny (Bilham *et al.* 2001; Bodin & Horton 2004; Mukherjee *et al.* 2013, 2015). The Early Tertiary was characterized by tensile to strike-slip stresses due to rifting, which changed to compressive to strike-slip stresses from the Miocene Himalayan collision onwards (Bilham *et al.* 2001; Misra *et al.* 2014, 2015, **2016**).

Comprehending the tectonics of the Deccan Traps, which outcrop mainly in the Indian states of Maharashtra, Gujarat, Madhya Pradesh, Andhra

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Pradesh and Karnataka, is also crucial in deciphering how the Seychelles microcontinent rifted from India, with implications for offshore basin and continental margin evolution around the northern Indian Ocean.

This Special Publication contains 13 research papers on the tectonic aspects of the DLIP, commonly referred to as the Deccan Traps. The broad perspectives of these papers include field-based structural geology, geochemistry, analytical models, the relationship of geomorphology to structure and tectonics, and geophysics (palaeomagnetism, gravity and magnetic anomalies, and seismic imaging), with respect to both palaeo- and neotectonics. These papers develop the relatively neglected tectonic investigations of the Deccan LIP and demonstrate that it is important to understand the structure and deformation of the province as well as the petrology, which has been well studied over many years.

Overview of the tectonics and structural geology of the DLIP

Madagascar, Seychelles and India constituted a single large continental block until Cenomanian–Turonian times. Madagascar rifted from India at about 90 Ma. In a subsequent rifting event at about 63.4 Ma, the Seychelles microcontinent and the Laxmi Ridge, a microcontinental block now located between India and Seychelles, rifted from India. This rifting event of the Laxmi and Seychelles microcontinents was almost coeval with Deccan flood volcanism (reviewed in Bhattacharya & Yatheesh 2015). Geophysical studies have been already conducted to ascertain the thicknesses of the trap/crust/lithosphere, the basement configuration and mantle anisotropies (reviewed in Misra 2015). The elastic thickness (T_e) of the plate beneath the Deccan Traps is *c.* 8–10 km (Tiwari & Misra 1999). The anomalous gravity high in the Mumbai coastal area indicates either a shallow secondary plume that supplied lava for the Deccan volcanics (Negi *et al.* 1992) or a bolide impact at around the K–T boundary that might have triggered Deccan lava eruption (Negi *et al.* 1993). By contrast, Sethna (2003) considered acid volcanic rocks, and Bhattacharji *et al.* (2004) mafic bodies, to give rise to the anomalous gravity high. Flows in the Deccan Traps are mostly sub-horizontal (Watts & Cox 1989), although Devey & Lightfoot (1986) deciphered a regional ‘very open’ antiform around Panvel (Maharashtra, India), along which the Deccan lava layers steepen to constitute the Panvel Flexure.

Regional faults have been identified in the north and west Deccan Traps from geophysical and remote sensing studies (Fig. 1; Harinarayana *et al.* 2007; Chandrasekhar *et al.* 2011; Kumar *et al.* 2011). The Cambay rift is bound by NNW-trending faults affecting the Deccan Traps (Dixit *et al.* 2014). The east–west-trending Tapti Fault defines the north boundary of the main outcrop of the DLIP (Azeez *et al.* 2011). The west coast passive margin is defined by the NNW-trending West Coast Fault (Fig. 1; Chandrasekharam 1985; Biswas 1987). The location of this fault is debatable because compelling field evidence is difficult to obtain. The Western Ghat escarpment (Figs 2 & 3; Kale 2010) is defined by a sharp change in topography, with the eastern side uplifted by 800–1200 m. This escarpment is considered to be a rift-bounding fault of the west coast passive margin (Gunnell & Fleitout 1998). The NNW-trending Koyna Fault parallels this escarpment. The Kurduwardi Lineament is another important structural element (Peshwa & Kale 1997). The northernmost region of the Kurduwardi Lineament is manifested by a NW-trending >20 km long series of fractures/faults in Thane district (Maharashtra State, India) (Peshwa & Kale 1997). Slickensides have developed over the fault planes. These faults have a *c.* 10–30 m throw and indicate both dextral and sinistral shear. Flexure, indicated by gently dipping flow layers (Fig. 3) related to the West Coast Fault, opened fractures that were subsequently filled with igneous material to form dykes (Peshwa & Kale 1997). Dessai & Bertrand (1995) and Hooper *et al.* (2010) reported north–south shear zones from the Deccan coastal areas, extending for *c.* 40 km from Murud to Mumbai (Fig. 4). Dessai & Bertrand (1995) reported steep fault planes with subvertical displacement and occasional slickensides. Hooper *et al.* (2010) established that the earliest (66–65 Ma) dykes have been sheared and that the later dykes were oriented either along the shear planes or intruded into them.

Why study structures in the DLIP?

The structural and tectonic features of the Deccan region have significant economic and societal importance and the region includes the important city of Mumbai and its hinterland. Basin development and the locations of fractures and faults in the DLIP have far-reaching implications in hydrocarbon exploration (Pandey & Agarwal 2000). There are four petroliferous basins in India within the DLIP: the Barmer, Kutch, Cambay and Mumbai shelf basins. The Deccan synclise and Saurashtra basins have also been studied for the occurrence of hydrocarbons. The area is important for groundwater resources and the Deccan structures are important for groundwater exploration (Rai *et al.* 2011). The seismicity of the area is a concern and the region around Koyna in the Deccan Traps suffered

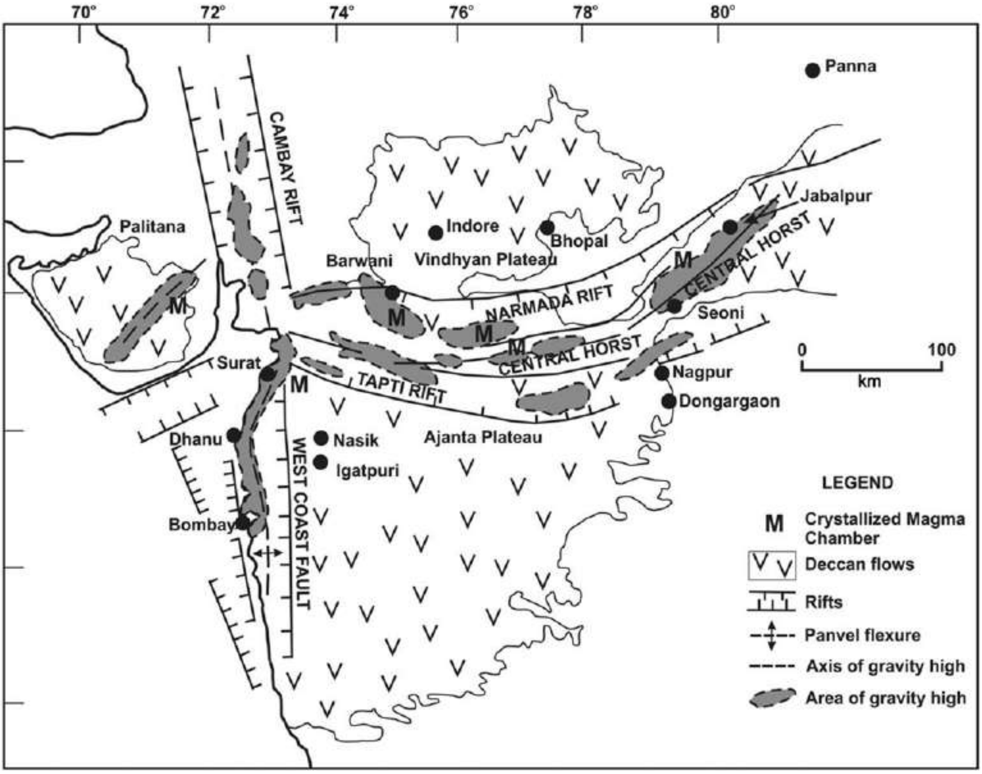

Fig. 1. Major tectonic elements of the Deccan large igneous province as deciphered from geophysical studies. Note the gravity anomaly highs associated with each of the rift zones (modified from Bhattacharji *et al.* 1996).

seismicity in 1967, possibly because of seepage-induced reactivation of the fault zone, which received global attention. Structural geological and tectonic studies can, in the long term, indicate the subsurface structures of the Deccan Traps as an important input into seismic studies, including the identification of seismic risk. Structural and tectonic studies will be better able to constrain possible locations for carbon sequestration in the Deccan Traps (Jayaraman 2007).

Content of this edited book

Detailed geomorphologic and morphometric studies of river networks within the area underlain by the Deccan Traps are presented by **Kale *et al.* (2016)**. This study indicates that the Western Upland region of the Deccan Plateau consists of at least three blocks with dissimilar Quaternary uplift histories. The authors therefore argue that the classical thought that the Deccan Traps are structurally monotonous is incorrect. **Mitra *et al.* (2016)** document smectite and kaolinite variations associated with faults bounding the Matanomadh Basin in Gujrat and use alteration patterns to interpret the presence of a palaeoslope created by Cenozoic rifting, through which water flowed and selectively weathered the basalt lavas. **Pathak *et al.* (2016)** studied 37 lava flows in the eastern DVP by palaeomagnetic methods. Their virtual geomagnetic pole positions indicate a brief eruption period at the Cretaceous–Palaeogene boundary in the eastern and western Deccan Traps. The western Deccan Traps are near the west coast of India and their eastern counterparts are at the easternmost extreme of the DLIP. The virtual geomagnetic pole position does not indicate a brief eruption period around the Cretaceous–Palaeogene boundary, but represents a record of the past geomagnetic field direction at the sampling site/location during the interval of time over which the characteristic remnant magnetization directions were acquired. **Nemčok & Rybár (2016)** describe the rift–drift transition processes and their controlling factors in the magma-rich Gop Rift–Laxmi Basin that predated the Deccan eruption event. Details of the documented break-up mechanism apply to magma-rich break-ups worldwide.

Fig. 2. View of sub-horizontal lava flows of the Deccan large igneous province looking towards the west from Lion Point in Lonavala, *c.* 100 km east of Mumbai. This location is on the top of the Western Ghat Escarpment; Photograph by Achyuta Ayan Misra.

Misra *et al.* (2016) studied carbonate seismic facies and subsidence on the ridges in the NW Arabian Sea to analyse how the Deccan mantle plume affected the tectonics of the offshore region of the DLIP. **Gupta *et al.* (2016)** detail seismicity based on several geophysical techniques in the Koyna region, where the periodic loading and unloading of water has been envisaged for seismicity induced by artificial water reservoirs since 1967. Their preliminary borehole investigations revealed faults and foliation planes and more detail is expected from this research group in the coming years regarding subsurface structural geology at Koyna. Analyses of P-wave receiver functions by **Mandal (2016)** enabled him to delineate the crust–mantle structure below the Kutch rift zone. He attributed this complex structure to be a key causative factor of the recent lower crustal seismicity in the region. **Rajaram *et al.* (2016)** performed detailed magnetic studies on part of the Deccan Traps and identified seven subsurface lineaments. They correlated these lineaments in the magnetic anomalies with already known brittle shear zones, faults and river courses. Identifying such lineaments can pinpoint unrecognized fault or shear zones, or sediment-filled basins, underneath the Deccan basalt cover. **Maurya *et al.* (2016)** reviewed the neotectonic roles of active faults (Mukherjee 2013, 2014*a*, *b*, 2015, **2016**) in the Kutch basin with respect to the post-Deccan Traps inversion of the Kachchh basin and the present day seismicity. With the help of ground-penetrating radar, they also documented a few subsurface faults. Such studies can correlate the lineaments in studies such as **Rajaram *et al.* (2016)**.

Several papers are concerned with the field and structural interpretation of basaltic dykes associated with the DLIP. The field structural studies of **Misra & Mukherjee (2016)** revealed differences in the structural deformation of different age groups of basaltic dykes in the province. An older *c.* 65.5 Ma group of dykes (Group I) are faulted/sheared and lacking in a uniform trend. Younger *c.* 65–63 Ma groups II and III dykes are syn- to post-deformation intrusions and intrude into the faults/shears. They point out that, in addition to the dyke trends, the

Fig. 3. Southern ridge of the *c.* 1000 m high Matheran Plateau showing sub-horizontal to gently dipping flows of the Deccan large igneous province. View looking towards the south; Photograph by Achyuta Ayan Misra.

Fig. 4. A typical wave-cut platform at Janjira-Murud *c.* 140 km south of Mumbai along the west coast of India. This view looking towards the south shows the hilly terrain around the area and the Janjira sea fort in the background. Such sub-horizontal exposures along rocky stretches provide a wealth of geological knowledge on the tectonics of the Deccan large igneous province (e.g. Dessai & Bertrand 1995; Hooper *et al.* 2010; Misra *et al.* 2014; **Misra & Mukherjee 2016**). Photograph by Achyuta Ayan Misra.

direction of the Seychelles–India separation can also be studied from the attitude of the brittle shear planes within the Deccan Traps. The analytical modelling of **Ju *et al.* (2016)** explains how propagating dykes deflect due to mechanical layering in the crust. They also postulate a four-stage evolution of the dykes from the Narmada rift zone. **Kaplay *et al.* (2016)** report dykes from the Kinwat region in the eastern part of the Deccan Traps. Based on the occurrence of faults and lineaments, the authors consider Kinwat to be a future location of intraplate seismicity. **Babar *et al.* (2016)** report brittle-sheared NE-trending dykes from the Aurangabad region that match the trend of the Narmada–Tapti lineament. They also report on field studies of the local directions of lava flows.

The collection of papers in this volume provides new insights into the structural features and the tectonic evolution of the DLIP. This provides an impetus for further field geological and geophysical studies. The main findings include: evidence that the DLIP is divisible into a number of structural blocks separated by faults, rather than being a single coherent block; interpretation of the rift-induced palaeotopography, which provides further constraints for the eruption period; details of how continental rifting occurs in magma-rich systems; the role of the Deccan/Réunion plumes in the tectonics of the DLIP; the emplacement of dykes with different time and structural relationships to faults and shear zones from borehole studies; the demarcation of the crust–mantle structure; the identification of subsurface tectonic boundaries; and basin inversion after Deccan basalt eruption. This volume provides an impetus for further field-based geological and geophysical studies of this important province.

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